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7. How to Improve the Quality of Broadleaved Seedlings Produced in Tree Nurseries

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Summary

Broadleaved seedlings grown in tree nurseries contribute to forest sustainability in three ways. First, commercial plantations established from nursery stock provide wood products used by society and associated economic benefits. Secondly, seedlings used to establish community forests support the need for wood that is consumed locally or is manufactured and sold to the direct benefit of those in the community. Thirdly, broadleaved nursery stock production can also promote forest sustainability by conserving local genetic sources of indigenous species that might otherwise be lost.

Producing nursery stock of a desired size requires balancing environment conditions between those favouring growth and those which hold growth back, while avoiding severe infestations by harmful insects and disease. Nursery stock needs to meet certain size targets to be successful after planting, however, physiological properties are at least equally important to field performance. Nonetheless, practices to produce seedlings possessing desirable physiological traits remain beyond the reach of most nursery managers. Physiological criteria of stock quality are available but their adoption as grading standards seldom occurs without the support of those who are responsible for tree survival after planting. The development of morphological and physiological standards that are based on field performance and related back to nursery production practices is an important element of the improvement of reforestation success using broadleaved tree species.

Keywords: nursery stock production, forest sustainability, target seedling, standard, field performance.

Introduction

It is questionable whether forests could be managed sustainably without the planting of seedlings grown in tree nurseries. Forest management can be said to be sustainable if it provides "generational equity" (Fox 2000). With generational equity, forest management is sustainable if it meets the present needs of society without compromising the ability of future generations to obtain the same levels of benefits from the forest (American Forest and Paper Association 1999). Tree nurseries provide planting stock that helps ensure desired tree species are regenerated rapidly following disturbance. Three areas can be identified in which the nursery production of broadleaved tree seedlings produced in nurseries contribute to sustainability: plantation forestry for industrial wood production, community forests where the benefits of the forest are realized locally, and for the preservation of rare or threatened species and genetic sources.

The demand for forest products is increasing in tandem with global population while the area of forest in the world is declining (Hee 1993). To satisfy the growing demand for forest products from a shrinking forested landbase, countries will increasingly turn to intensively managed forest plantations. Plantation forests provide jobs, improve national economies, and provide wood that might otherwise come from natural forests. Plantations are usually established using seedlings or cuttings produced in tree nurseries and using seedlings with high growth potential helps maximize wood production.

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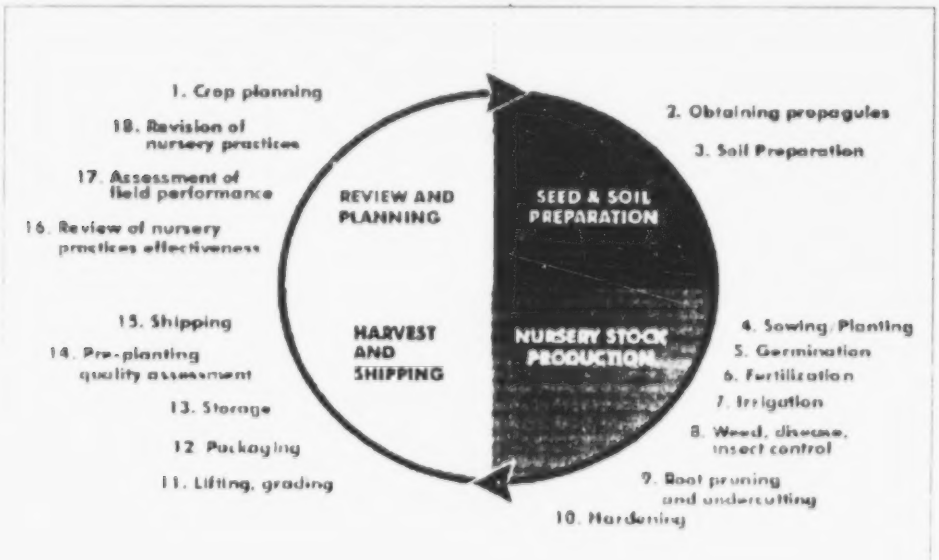
In contrast to industrial plantations, community tree nurseries produce seedlings to satisfy local needs for forest products. Community nurseries are usually smaller than nurseries producing seedlings for industrial plantations, the former growing hundreds or thousands rather than millions of seedlings in the latter. The seedlings grown in community nurseries produce trees for planting to provide building materials, food, and wood for fuel.

Forests also provide benefits that are not usually accounted for in financial terms. Forests protect watersheds, provide homes for wildlife, and act as a reservoir or preserve for native plant and animal species. In addition it is increasingly being recognized that many forest dwelling plants and animals contain biochemicals with properties valuable to society (Kimmins 1997) or have genetic properties that have value for breeding purposes or as a source of genes for other species (Namkoong 1986). Nascent efforts in ecological restoration and genetic conservation can be supported by nurseries which have the ability to produce tree seedlings of a wide range of forest plant species (Landis et al 1993, Edson et al 1994). While nursery propagation of rare species is not a replacement for habitat preservation, efforts in restoration will be aided by an improved understanding of the seed germination and nursery cultural requirements of the many infrequently grown species.

The practices employed to produce nursery stock can affect survival and growth after planting (Duryea 1985). Although the importance of sound nursery practices to sustainable forestry is often implicit, there is a direct link between nursery practices and whether many of the objectives of sustainable forest management are achieved (Persson 1991). Nursery practices may vary in intensity depending on whether trees are grown for industrial plantations, community forests, or to preserve species and genetic resources. Regardless of the end-use of the trees, there are common aspects of nursery practices inherent to a sound approach to seedling production.

Nursery stock production

Nursery stock production can be categorized into four phases and a number of attendant steps (Figure 1). As defined here, this process includes the planning for production and shipping, and is not limited to steps that are directly involved with germination and growth of seedlings. Detailed information on each phase is described elsewhere (e.g., Armson & Sadreika 1974, Landis et al 1995). This paper will highlight some key aspects of nursery stock production that are essential for the success of tree seedling production and reforestation.



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Soil preparation and seed germination

The two major preparatory steps in producing tree seedlings are to prepare the soil for planting and to obtain viable seed (or vegetative propagules if plants are being grown vegetatively). Mismanagement of either of these steps will usually create major impediments to the production of vigorous tree seedlings.

Whether seedlings are grown in containers or bareroot nursery fields, in order to grow vigorous trees the soil must provide adequate water, inorganic nutrients, and aeration. Armson and Sadreika (1974) stated "the growing of trees in a nursery involves an intensive form of management, particularly when the nursery is to be in continuous production for many years. Although all phases of production are important, it is the soil and the practices dealing with it that are the core of any management program." While proper soil preparation is vital, soil properties are more easily controlled than seedling properties since soil reactions are based on physical and chemical characteristics.

In the case of seed, physiological processes regulate viability and dormancy. Seed that is nonviable will not germinate; viable seed that is dormant will not germinate rapidly or uniformly. Slow germination is a problem if the trees do not reach the size desired for planting.

Slow germination is often accompanied by germination that is spread out over a long period of time. A wide spread in the time of germination among seedlings can create serious nursery crop management problems if it causes large size disparities among seedlings in a nursery crop. Small initial differences in size due to variable germination can lead to large size differences at the time of shipping. Seeds that germinate later may produce seedlings that are overtopped by earlier germinating seedlings, reducing light levels and therefore limiting photosynthesis in the smaller trees, leading to yet greater differences in size.

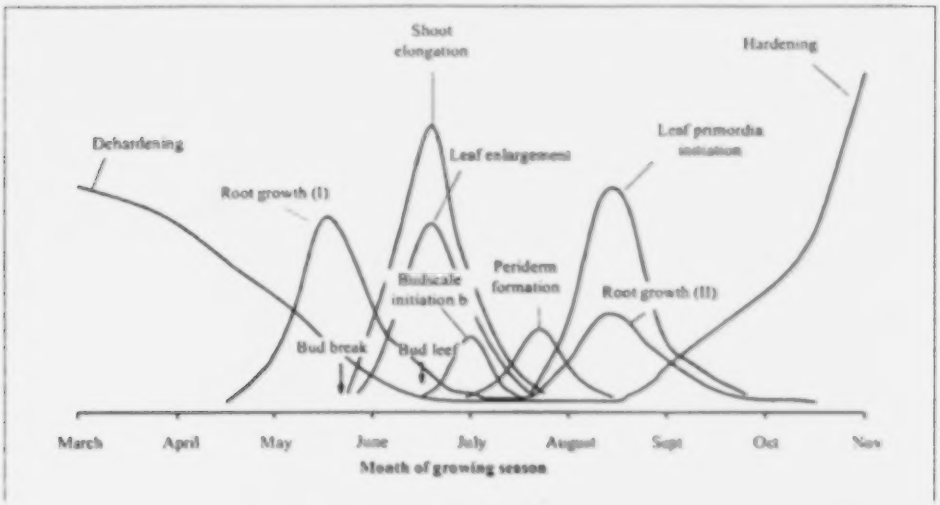
In a container nursery, differences in time of germination within a crop can lead to large differences in leaf area and therefore transpiration, which cause differential rates of container drying. The driest containers can determine the watering rate in a crop. Since all containers in a crop are usually watered at the same time, the larger seedlings will be watered closer to their optimum and the growing medium of the plugs of shorter seedlings will tend to be too wet. This situation is exacerbated by two factors: being in an understory the shorter seedlings transpire less because of lower light levels, This also tends to keep the growing medium in the container wetter. Secondly, if overly wet the growing medium may become anaerobic due to flooding which causes stomata to close and seedling transpiration to be restricted. Finally, the cooler, wetter understory environment experienced by the smaller seedlings in a crop favour disease that can have serious consequences for crop management and seedling quality.

Seedling growth

As for seed and seed germination, the science that underlies the growth of seedlings in a nursery is very complex, although the act of growing seedling crops is not viewed that way. This complexity is illustrated in Figure 2, which shows some of the overlapping and, in part, interconnected growth events that take place in typical northern temperate hardwood tree seedlings during the growing season. Cold hardiness declines in the spring and root growth commences prior to bud break. With bud break the predetermined leaves and telescoped shoot tissues inside the bud enlarge. For species in which the shoot grows from predetermined tissues, the terminal bud begins to form while the current year shoots are elongating. Budscales form, leaf primordia that will expand in the following year are initiated inside the bud, and a periderm develops on the exterior of the stem as the current year's shoot ceases elongation. Often, there will be an autumn resurgence of root growth in broadleaved seedlings when shoot growth ends. These complex and interconnected, growth processes occur as a result of biochemical and physiological that are ultimately governed by genetic responses to seasonal environmental cues.

One of the reasons nursery stock production is not viewed as highly complex is that seedlings "grow themselves", with relatively little effort on the nursery manager's behalf. As a result, producing a crop of seedlings does not require that one be aware of all the steps that a tree passes through during a growing season. In general nursery management practices are main-

ly intended to control the size and relative balance of shoot and root tissues by varying fertilization rates, watering, shoot and root pruning, and in the case of seedlings grown in greenhouses, the daylength and temperature.
An ability to control the size and balance of a crop of seedlings is the minimum that should be expected of a nursery manager. However, enough is known about the physiological traits important for planting success that nurseries can potentially produce seedlings with particular physiological traits. That this is not standard practice is the result of a variety of factors and there are notable exceptions (Sloan 1994).



Among the most factors impeding the production of seedlings with specific physiological traits is a tendency to view the time seedlings are shipped from the nursery as the end rather than the continuation of the nurseries responsibility that is then shared with those that plant trees. Ideally, nursery managers will have a sound understanding of the relationship between the physiological responses of trees to the nursery environment. A basic background in horticulture can provide much of this knowledge (Landis 1994). However, those who plant trees, including most foresters, usually have only a rudimentary training in ecophysiology. Thus, most foresters lack the knowledge to be able to relate the properties of nursery stock to the site and environmental conditions into which the trees are planted. As a result there is little chance of feedback from the field to the nursery to improve the properties of seedlings being planted (Colombo & Parker 1999).

Shipping and planting

Trees lifted at the completion of the seedling production phase are either stored or shipped immediately for planting. Many of the problems affecting seedlings occur during this time, especially with bareroot seedlings because the roots are exposed and may dry after lifting and long roots are cut off. If lifted seedlings are to be stored indoors overwinter it is essential that they acquire sufficient hardiness before being removed from the nursery beds. This requires an understanding of the processes that lead to high levels of cold hardiness in roots and shoots as well as a means of determining when seedlings can be stored.
Pre-planting quality assessment should be the keystone event in nursery production. Nursery practices determine seedling size and physiological characteristics. The link between nursery practices and the quality of seedlings should be obvious, yet this relationship is often overlooked. Part of the reason for it being overlooked may be that the economics of production

focuses attention towards producing **more** seedlings, rather than on producing **better** seedlings. The other cause of a lack of focus on quality is that most foresters receiving seedlings are only concerned that the trees meet minimum criteria for size. Pre-planting quality assessment is a means of evaluating aspects of seedlings that go beyond size.

Table 1 lists some of the more commonly evaluated seedling quality attributes (Colombo et al. 2001). These attributes can be broadly classified as those based on morphology and those based on physiology. Puttonen (1987) spoke in favour of morphological attributes as a predictor of field performance, in part because morphological characteristics are widely measured and are known to bear a relationship to field performance (Thompson 1985). However, as noted by Duryea (1985), stocklots that have the same size seedlings may differ in important physiological characteristics (in the extreme case, one group may contain undetected damage or even dead trees and yet have the same morphology). Some physiological tests can discern damage as well as indicate the vigour of nursery stock. Nursery mangers should seek to produce seedlings that have desirable morphological properties and also perform well in physiological tests.

Root growth potential and chlorophyll fluorescence are physiological tests that can be used both to detect damage and to rate healthy seedlings into vigour classes. Root growth potential is probably the most commonly measured physiological quality assessment method. It integrates the ability of the roots to conduct water and the shoot to photosynthesize, two crucial aspects affecting seedling performance after planting (Ritchie & Simpson 1997).

Chlorophyll fluorescence takes place when a beam of light is shone on green plant tissues. The amount of light fluoresced and its pattern over time indicates whether chlorophyll molecules are intact and the photosynthetic mechanisms are active and undamaged. This is also an attractive test because it is non-destructive, the results are instantaneous, and the test simple to conduct (Sampson et al 1997, Colombo et al 2001).

The measurement of stress-induced volatile emissions (SIVE) is a promising pre-planting test for detecting stock with viability problems or tissue damage (Sampson et al 1997, Colombo et al 2001). Trees and other plants respond to a damaging stress by producing characteristic gases (Kimmerer & Kozlowski 1982). One of these gases, ethanol, is a byproduct of anaerobic respiration. Damage to the aerobic respiratory pathway or a lack of oxygen can lead to anaerobic respiration. Correlations between ethanol production by seedlings and damage to them have been demonstrated (Templeton & Colombo 1995).

Electrolyte leakage is another method that can detect tissue damage (Murray et al. 1989, McKay & White 1997). Damaged tissues leak electrolytes from cells that show up as increased electrical conductivity if the tissues are immersed in water. Electrolyte leakage has been used extensively to detect post-freezing damage which indicates the level of cold hardiness and readiness for frozen storage (Glerum 1985, Deans et al 1995). Electrolyte leakage has also been used as a viability test to detect damage to tissues prior to shipping seedlings for planting (McKay & Mason 1991, O'Reilly et al 2000).

Relationships between field performance and the physiological and morphological properties of nursery stock need to be established separately by species. By tying nursery stock properties to field performance and nursery cultural practices it is possible to implement practices that will more consistently produce nursery stock possessing higher levels of desirable attributes. Unfortunately, it has been argued that the failure of stock quality tests to infallibly predict field performance is reason not to use such tests as a grading procedure (e.g., Binder et al 1988). Such pernicious arguments disregard the benefits to regeneration programs that come from morphological and physiological grading of nursery stock. Although the field performance of any particular stocklot is not highly predictable (because of variability in handling, planting, and field conditions), stocklots with high root growth potential and chlorophyll fluorescence should on average perform better after planting. Certainly, it is difficult to imagine many foresters willingly accepting nursery stock with lower root growth potential and chlorophyll fluorescence if such stock is provided at a competitive cost.

Diameter	Bud initiation	Chlorophyll fluorescence	Bud dormancy status	Micro-nutrients	Amino acids	Insects
Dry weight	Leaf primordia	Electrical impedance	Cold hardiness	Nitrogen	Carbohydrates	Pathogens
Height		Photosynthesis	Damage expression	Phosphorus	Plant growth regulators	
Ratio measurements		Plant moisture status	Root growth potential	Potassium		
Root system size			Stress-induced volatile emissions			

Review and planning

Review and planning need to take account of what takes place in the nursery as well as how seedlings perform after planting. Through review and planning it is possible to link results not just between one nursery crop and the next but also between the nursery and the field. Improvement over time requires good record keeping and a review of those records alongside evidence of field performance.
There are three components of Review and Planning identified in Figure 1.

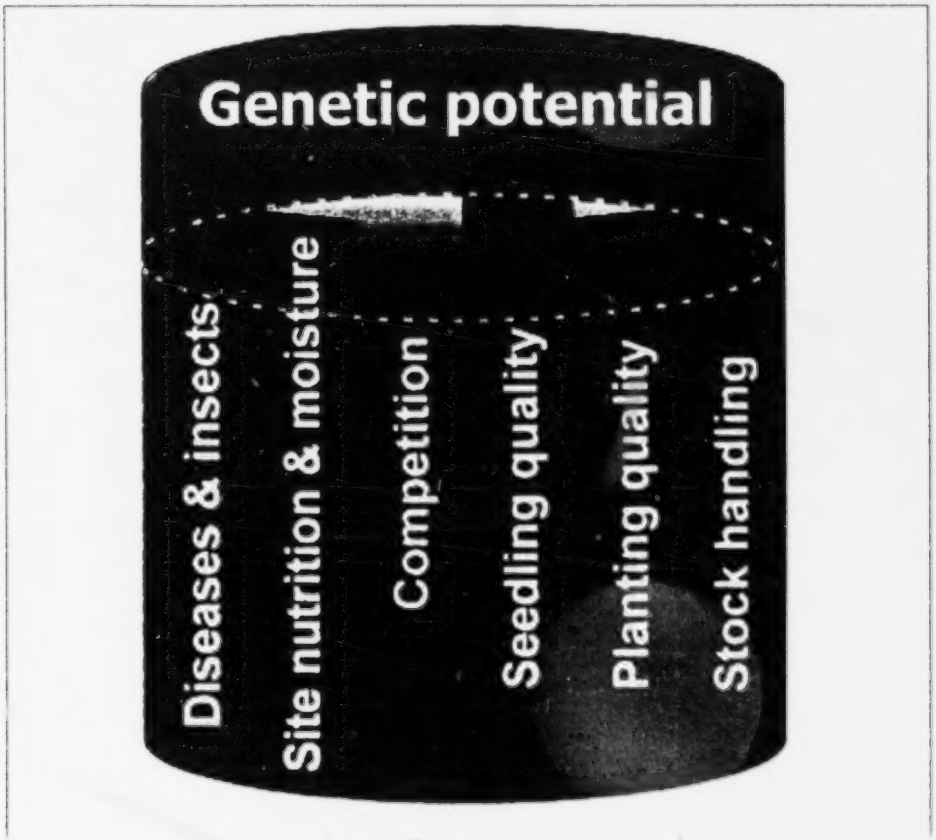
- The review of nursery regime effectiveness involves a retrospective analysis within the nursery that relates the size and condition of seedlings achieved in light of the practices that were employed. It relates, for example, whether seedlings met prescribed sizes and were ready for shipping when needed.
- Field performance is assessed to determine how well the seedlings met the objectives for which they were grown. It is important for the nursery manager to determine what role the manner in which the trees were grown and the condition of the seedlings when shipped played in the success of the stock after planting.
- Crop Planning is done by the nursery manager taking into account the practical, day-to-day human, financial and biologial considerations that affect how a crop if seedlings will be grown.

Landis (1994) states that seedlings belong to the customer, not to the nursery where they were grown. Therefore, planning needs to be done foremost from the perspective of the person who will be receiving the trees and only thereafter from the perspective of the nursery manager. Field performance, therefore, needs to be a critical part of planning, although in practice this is too often overlooked.

Relating field performance to nursery practices

One way to promote the use of nursery practices that improve seedling physiological and morphological traits is to draw explicit links between the manner in which nursery practices affect these traits and how the traits affect survival and growth after planting.
The field performance of planted tree seedlings can be considered in light of Liebig's Law, which states that the productivity and ultimately the survival of a complex system that is dependent on a number of essential inputs are limited by the single variable in least supply. This concept was restated by Odum (1971) for ecological systems and by Landis (1993) for tree seedling production. This concept can also be applied to the issue of seedling performance af-

ter planting (Figure 3). Unrestrained by external factors, the growth of a seedling is limited only by the genetic potential to utilize carbon dioxide, water, and mineral nutrients. However, planted seedlings seldom achieve their genetic potential as growth is usually subject to a number of limiting factors. The relationship between seedling quality and field performance shown in Figure 3 is represented in terms of staves in a barrel. The top of the barrel is seedling genetic potential, while seedling performance after planting is shown by the height of water, which is determined by the shortest stave in the barrel. Nursery managers should produce stock where seedling quality is not the factor limiting field performance.



To evaluate whether seedling quality is limiting to field performance it is necessary to: a) understand the relationship between seedling quality traits and performance under a range of field conditions, b) have a program where seedling quality is monitored prior to planting, and c) collect data on field performance and relate it back to seedling quality. In practice, these three steps are seldom all carried out. Consequently, the relationships between nursery practices, seedling quality, and field performance are usually not well understood.

One of the impediments to understanding how field performance is affected by nursery practices is the variation in field environments that obscures such relationships. As a result, seedlings of similar quality may perform very differently when the field conditions they are planted into are dissimilar. In the alternate situation, seedlings of diverse quality may perform similarly under certain field conditions; either very harsh conditions, where all stocklots are li-

able to perform poorly regardless of quality, or very forgiving conditions, where almost all stock will perform well. The majority of research on seedling quality and field performance has been conducted using conifer nursery stock. While the principles are likely the same the specific relationships between seedling quality and field performance undoubtedly need to be verified and fine-tuned for broadleaved species. Three approaches that can be used to reveal relationships between seedling quality and field conditions are: a) evaluating seedling performance under limiting environmental conditions in test environments; b) planting seedlings with a known gradient in quality on a semi-controlled site; and c) boundary line analysis of field performance data from operational stocklots.

In the limiting conditions approach, seedlings are evaluated after planting in an artificial harsh environment. Seedlings that perform better in this harsh test environment are concluded to be better adapted to the anticipated non-ideal site condition. This approach, proposed by Timmis (1980) and applied by Grossnickle (Grossnickle et al 1988, Grossnickle & Folk 1993), has been used to evaluate the performance potential of seedlings in controlled environments mimicking expected limiting field conditions (e.g., hot or cold, dry or wet).

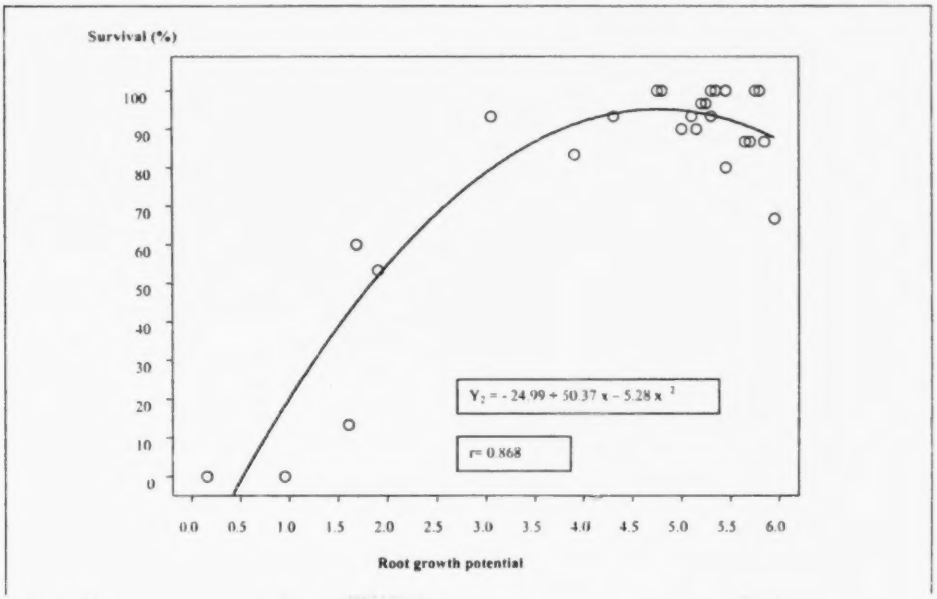
The limiting conditions approach is similar to the vigor testing procedure developed at Oregon State University (McCreary & Duryea 1985). The OSU vigor test is based on the premise that less vigorous and damaged seedlings can be killed or further damaged by stresses experienced during planting and establishment. These susceptible stocklots can be detected prior to planting by applying an artificial stress and monitoring the stock for survival in a growth room. Good correlations have been found between survival of the OSU stress test and field survival and growth (McCreary & Duryea 1985), although in planting years with non-stressful weather poorer stock has been found to survive and grow adequately.

A second approach used to relate seedling quality to field performance is to compare the performance of seedlings with a gradient in a chosen stock quality attribute. In this way a range of seedling sizes or physiological conditions is created while attempting to remove other variations in seedling quality or planting site conditions that may obscure the relationship There are two keys to relating a quality gradient to performance potential of a stocklot. One requirement is that the gradient in quality be broad enough to produce a wide range of a difference in performance potential. If the stock is all of about the same quality then much of the data will be clustered together and correlations will not be evident (McCreary & Duryea 1985). The second key to using the gradient approach is to minimize interference from extraneous factors that might obscure the relationship between the measured quality attribute and field performance. For this reason such tests are often conducted using a single stocklot and partially controlled conditions where extreme competition or environmental conditions can be avoided. An example of this approach is shown in Figure 4, where a range of root growth potential levels was created by storing and/or moisture stressing the trees before planting. Seedlings were from the same stocklot and planted at the same time, so that differences in field performance could be deemed to be due to differences in root growth potential. This data demonstrates a significant relationship between RGP and survival after planting (Figure 4). Similar relationships have been produced for other species and attributes (Mullin & Christl 1982, Ritchie 1985).

A third means of determining the relationship of seedling attributes to field performance is through boundary line analysis (Webb 1972). Boundary line analysis can be used to identify a functional relationship amidst variation due to unidentified factors by isolating the top-performing points in each seedling quality class. According to boundary line theory, the level of a variable, y, which is dependent on a second variable, x, can be reduced from its optimal level by unidentified factors. Boundary line analysis has been used to determine relationships where the unidentified factors cannot be adequately known and their cumulative effects are not quantifiable (Kitchen et al. 1999).

Figure 5 shows an example of boundary line analysis. This example uses data from a trial where white spruce bareroot seedlings were graded into a range of size classes based on root length prior to planting. Tree heights were measured five years after planting. Figure 5a shows the correlation derived from individual tree data, which produced a large cloud of points and a weak correlation (r^2=0.167). Figure 5b shows the correlation produced using average root length classes rather than individual tree data. The increase in the value of the correlation co-

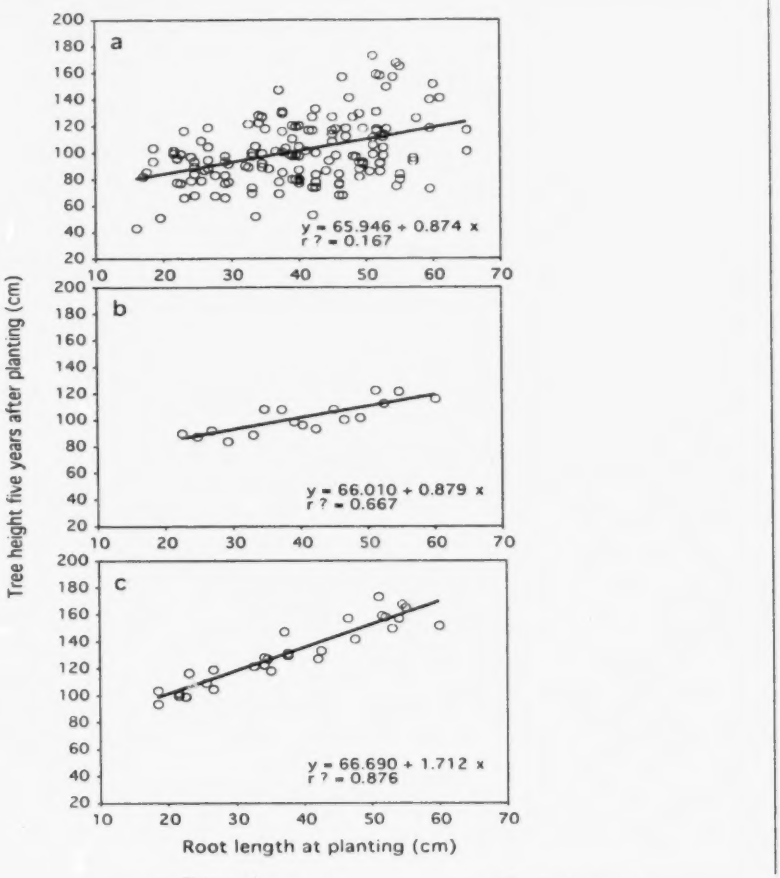
efficient (r^2=0.667) reflects the reduced variation due to averaging and produced essentially the same equation for the relationship as the individual tree data. In comparison, using boundary line analysis (Figure 5c) a regression line was fit to the topmost individual-tree data points in each root length class. This boundary line relationship was significant (r^2=0.876) and the larger slope indicated a stronger dependence of field performance on the root length of seedlings at planting. Boundary line analysis is a means of analyzing the large amounts of field performance and seedling quality data that are sometimes available from plantations established for industrial purposes. The technique offers a means of sorting through the variability in nursery stock performance that occurs under operational field conditions and stocklots from a range of genetic sources and raised and planted in different years.



Recognition that what takes place in the nursery affects seedling performance after planting is not new (Shirley 1939, Wakely 1949). Attempts to improve field performance have been the main spur to implementing or refining morphological standards for planting stock (Thompson 1985), although such size standards often have been based on perception rather than demonstrated relationships between size and field performance (Sutton 1980). While seedling morphology is widely used to grade nursery stock, physiological standards have seldom been adopted (Dunsworth 1997). Sutton (1980) concluded that "attempts to improve planting stock quality will succeed only by unlikely chance unless they are based on adequate physiological knowledge". More widespread acceptance by foresters and nursery managers of the need for physiological standards is a prerequisite to the development of nursery practices that favour better physiological quality.

Conclusions

The greatest emphasis on planning nursery operations and on seedling quality often occurs in nurseries producing seedlings for industrial purposes. This reflects the greater capital avail-


a
y = 65.946 + 0.874 x
r ? = 0.167
b
y = 66.010 + 0.879 x
r ? = 0.667
c
y = 66.690 + 1.712 x
r ? = 0.876
Tree height five years after planting (cm)
Root length at planting (cm)

able there for seedling production and in general, a better trained workforce. Probably the least sophisticated nursery practices are employed in community-based tree nurseries. However, in many cases the smaller number of seedlings in community nurseries may allow for closer attention that partially makes up for less advanced nursery technology.

There is room for improvement in practices in even the most advanced nurseries, especially insofar as gaining an understanding of the relationships between nursery practices and field performance is concerned.

Attempts to use tree nurseries to regenerate non-commercially valuable species is daunting given the potentially large number of species that can be confronted, many with unique or unknown biological needs for germination and seedling growth. Broadleaved species have important roles to play in sustaining the natural environment, providing economic benefits through forest plantations, and supporting indigenous populations who rely directly on forests for wood and other products. Clearly, the efficient nursery production of broadleaved seedlings that will survive and grow vigorously is an important component of forest sustainability. The improvement of reforestation success using broadleaved tree species relies on the development of morphological and physiological standards that are based on field performance and related back to nursery production practices.

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